

Travel Time Estimation

Travel Time Estimation from Multiple Data Sources

F. Soriguera, D. Abeijon, D. Rosas, L. Thorson and F. Robuste

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F. Soriguera (corresponding author), CENIT – Center for Innovation in Transport, Technical University of Catalonia (UPC), Jordi Girona 29, 2-A, 08034 Barcelona (Spain),
Tel:+34934137667, Fax:+34934137675, francesc.soriguera@upc.edu.

D. Abeijon, CENIT – Center for Innovation in Transport, Technical University of Catalonia (UPC), Jordi Girona 29, 2-A, 08034 Barcelona (Spain), Tel:+34934137667, Fax:+34934137675,
davidabei@hotmail.com

D. Rosas, CENIT – Center for Innovation in Transport, Technical University of Catalonia (UPC), Jordi Girona 29, 2-A, 08034 Barcelona (Spain), Tel:+34934137667, Fax:+34934137675,
dulce.rosas@upc.edu.

L. Thorson, CENIT – Center for Innovation in Transport, Technical University of Catalonia (UPC), Jordi Girona 29, 2-A, 08034 Barcelona (Spain), Tel:+34934137667, Fax:+34934137675, leif.thorson@upc.edu.

F. Robuste, School of Civil Engineering, Technical University of Catalonia (UPC), Jordi Girona 1-3, B1, 08034 Barcelona (Spain), Tel:+34934017104, Fax:+34934017264, f.robuste@upc.edu

ABSTRACT

Travel time is the best indicator of the level of service in a road link, and perhaps the most important variable for measuring congestion. This paper presents a method for estimating accurate travel times in toll highways using data from multiple sources, as loop detectors and toll tickets. The proposed methodology consists of a data fusion technique using different travel time estimations in order to obtain a more accurate fused value with less error than individual estimations by itself. Finally results obtained in the application of the methodology to the AP-7 highway, near Barcelona in Spain, are presented.

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ARTICLE TITLE

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Full Title: Travel Time Estimation from Multiple Data Sources

1. INTRODUCTION

Europe is involved in a restrain process in the construction of new road infrastructures. This limitation is due to environmental, land occupancy and budget restrictions. On the other hand, mobility demand is still increasing in all countries. This situation leads to congestion becoming an important problem. The road network management is then essential to optimize the usage of available infrastructures.

Travel time and travel time reliability are key factors in road management systems, as they are the best indicators of the level of service in a road link, and perhaps the most important parameter for measuring congestion [1]. Travel time estimation is necessary to assess the operational management and planning of a road network. Moreover, travel time information is the best and most appreciated traffic information for road users.

Most European countries (Spain, France, Denmark, Italy, Finland, United Kingdom, Sweden, the Netherlands, Norway and Germany) consider travel time as an emerging issue in Europe and acknowledge a growing demand for real time travel time information. Most of the Trans-European Road Network (TERN) in these countries is now covered by a travel time project [2].

From these experiences it can be concluded that the deployment of a travel time measurement system in a road network is a complex issue. There is not a unique methodology to be applied in all cases, due to different road characteristics, different traffic flow patterns, different surveillance equipments, budget and information limitations, etc. The key factor is to obtain the maximum accuracy from the available data. In this situation is where data fusion techniques play an important role.

Basically there are two methodologies to measure travel time in a road link: the direct measure and the indirect estimation. The direct travel time measure is based on measuring the time interval that a particular vehicle takes to travel from one point to another. The data collection techniques used in this case are the floating car data, the license plate matching or the AVI (Automated Vehicle Identification) from toll infrastructure. Travel time data is directly obtained from these measures. The alternative is the indirect travel time estimation from traffic flow characteristics (density, flow and speed), obtained from magnetic loop detectors. To obtain travel time data from these measurements some type of algorithm must be applied.

Because of the growing interest in measuring travel time, there have been several studies attempting to determine link travel times in a road segment. Previous research on indirect travel time estimation focuses on loop detector data, because loop detectors are currently the most widely used detection technology. Some of these methods are based on the speed estimation in detection points. These algorithms have been proven to be quite effective in road segments with high density of detection points and free flow traffic conditions, but they do not perform well in roads with a lower surveillance level or under heavily congested situations. Several authors have tried to develop better algorithms to overcome these limitations and problems in the spot speed estimation. [2-6].

A different approach to determine the link travel time from loop detector data is presented in [7], where a cumulative flow balance algorithm at successive detector sites is proposed. The counter detector drift is the problem in this case. Other studies, [8-10] focus their efforts on obtaining the detailed signature of a particular vehicle when crossing an inductive loop, so that this vehicle can be reidentified downstream. Another strategy in the identification of vehicles using loop detectors is the platoon recognition [11, 12]. These methods propose the

estimation of average travel time by matching unique features of vehicle platoons such as the position and/or distribution of vehicle gaps or unique vehicles.

Regarding direct measure of travel time, many advanced techniques have been applied [13]. For example [14-17] analyze the direct measure of travel time using AVI systems or [18] using video license plate matching. Other applied techniques are the electronic distance-measuring, automatic vehicle location, cellular phone tracking, video imaging, and so on.

This paper proposes an accurate travel time estimation method using multiple data sources. A spot speed algorithm and a cumulative flow algorithm are used to estimate travel times from loop detector data. Moreover a simple algorithm for estimating travel times in toll highways is developed: the algorithm uses the travel time data included in the toll tickets for different routes in order to estimate the section travel time between consecutive entry and exit ramps.

The paper is organized as follows: Section 2 describes the methodologies to obtain travel times from loops and section 3 presents the direct measurement travel time algorithm using toll ticket data. The main ideas of the data fusion method are outlined in section 4, and finally in section 5 a review of travel time dissemination technologies and some results of the application of the model to the AP-7 highway in Spain are presented. The paper finishes with some general conclusions.

2. TRAVEL TIME ESTIMATION FROM LOOP DETECTOR DATA

Indirect travel time estimation is based in the measurement of fundamental traffic flow variables (flow, speed and density) in a particular spot of a highway and the extrapolation of these point measurements to a stretch of the highway. These fundamental variables capture the whole

physical traffic process, and so it should be possible to determine any other variable from them. Loop detectors are the most widely spread technology to collect flow, speed and density of traffic. Take into account that single detectors only collect flow, and speed and density must be approximated. On the other hand dual loop detectors are capable of measure all traffic flow variables.

Travel time estimation from loop detector data is based in two basic methodologies. First and most widely used algorithm is the spot speed algorithm. The alternative consists on a cumulative flow algorithm.

2.1. Spot Speed Algorithm

As stated earlier this method is based in the speed measurement in a highway section by means of single or dual loop detectors. Travel time could then be obtained by simply applying the following equation:

$$t_{(i,t)} = \frac{l_i}{v_{(i,t)}} \quad (1)$$

Where: l_i is the length of the highway stretch considered to be associated with loop detector “ i ”.

$v_{(i,t)}$ is the average 5 minutes speed measured in loop detector “ i ” and time interval “ t ”.

$t_{(i,t)}$ is the average 5 minutes travel time in the highway stretch “ i ” and time interval “ t ”.

The hypothesis considered in the application of this algorithm is that traffic flow characteristics maintain constant in the whole stretch and in the whole time period. This means

that for the algorithm to be effective a high surveillance density (loop detectors every 500m) and a frequent actualization of parameters (every 5 minutes) are needed.

Moreover, in highly congested highways with frequent stop and go situations, travel time estimation using this algorithm can be very different from reality. To smooth this problem a calibration method is proposed. This calibration is based in averaging the measured speed in loop detector “ i ” and time interval “ t ” with previous measured speeds, in time and space. Then the spot speed travel time algorithm is finally formulated as follows:

$$t_{(i,t)} = \frac{l_i}{V_{(i,t)}} \quad (2)$$

$$V_{(i,t)} = \sqrt{V_{(i,t-1)} \cdot \sqrt{V_{(i-1,t)} \cdot V_{(i,t)}}} \quad (3)$$

Where: $V_{(i,t)}$ is the calibrated spot speed in loop detector “ i ” and time interval “ t ”.

FIGURE 1 Spot speed algorithm required surveillance configuration

2.2. Cumulative Flow Balance Algorithm

Due to the required high surveillance density and the lack of accuracy of the spot speed algorithm in congested situations, an alternative travel time estimation methodology is proposed. The cumulative flow balance algorithm estimates travel time directly from loop detector flow measurement, without the previous imprecise calculation of speed.

The algorithm uses the entrance and exit flows in the highway stretch to calculate the travel time using a simple flow balance method. The algorithm responds to the following equation:

$$S_{(i,t)} = S_{(i,t-1)} + \int_{t-1}^t (q_{i(i,t)} - q_{o(i,t)}) dt \quad (4)$$

Where: $S_{(i,t)}$ is the total cumulated vehicles in the highway stretch “ i ” and in the time interval “ t ”.

$q_{i(i,t)}$ is the entering flow in the highway stretch “ i ” and in the time interval “ t ”.

$q_{o(i,t)}$ is the exiting flow in the highway stretch “ i ” and in the time interval “ t ”.

Finally, travel time is calculated using equation (5):

$$t_{(i,t)} = \frac{S_{(i,t)}}{Q_{o(i,t)}} \quad (5)$$

Where: $Q_{o(i,t)}$ is the output flow of the main highway trunk in stretch “ i ” and in the time interval “ t ”.

Obviously, to apply this algorithm, all the highway ramps must be equipped with loop detector units. The surveillance scheme required is displayed in figure 2.

FIGURE 2 Cumulative flow balance algorithm required surveillance configuration.

This algorithm considers traffic as a continuous flow. Therefore the algorithm will be more efficient under heavy flow situations, and should not be applied when traffic flow is lower than 1500 veh/h/l (i.e. $Q_{o(i,t)} > 125$ veh/5min/l).

Note that to evaluate equation (4) it is necessary to establish an initial value for “ S_0 ”. This initial value is obtained from the average measured traffic density in the 5 minutes previous to the first 5 minutes time interval with a traffic flow “ q ” higher than 125 veh/5min/l.

$$S_{(i,0)} = K_{(i,-1)} \cdot l_i \quad (6)$$

$$K_{(i,-1)} = \sqrt{k_{i(i,-1)} \cdot k_{o(i,-1)}} \quad (7)$$

Where: $K_{(i,-1)}$ is the calibrated traffic density of highway stretch “ i ” in the 5 minutes time

interval previous to initial evaluation of the algorithm.

$k_{i(i,-1)}$ is the averaged 5 minute traffic density in the upstream loop detector.

$k_{o(i,-1)}$ is the averaged 5 minute traffic density in the downstream loop detector.

In case of using single loop detectors, traffic density has to be derived from the measured occupancy “ o ” (i.e. the percentage of time that the loop detector spot is occupied by a vehicle)

To approximate traffic density from traffic occupancy simply apply equation (8) assuming an average length of vehicles:

$$k = \frac{o \cdot L}{g} \quad (8)$$

Where: L is the length of the highway spot occupied by the loop detector.

g is the average length of vehicles.

3. TRAVEL TIME ESTIMATION FROM TOLL TICKET DATA

In direct travel time measurement, data is obtained by measuring the time taken for vehicles to travel between two points on the network. On toll highways, the data needed for the fee collection system, can be also used for travel time measurement.

On a highway with a “closed” tolling system, the fee that a particular driver has to pay at the toll plaza varies depending on his origin. In contrast, in an “open” highway system, toll plazas are strategically located so that all drivers pay the same average fee at the toll gate. In a closed highway system, each vehicle entering the highway receives a ticket (real -usually a card with magnetic band- or virtual -using an Electronic Toll Collection ETC device-), which is collected at the exit. The ticket includes the entry point, and the exact time of entry. By cross-checking entry and exit data, the precise time taken by the vehicle to travel along the itinerary (route) can be determined. Averages can be obtained from the measurements for all the vehicles

traveling along the same itinerary in the network. Two particular advantages of these measurements are the huge amount of data, since all vehicles have their entry ticket, and the continuous flow of real time data.

Toll tickets make it possible to measure travel time for all origin – destination relations on the highway. However, travel time data is obtained once the vehicle has left the highway. This involves a great delay in the information of long trips. Moreover, travel time for long trips can be increased by factors that are unrelated to traffic conditions, for example if the driver stops for a break or re-fueling. In order to reduce the influence of such events and the delay in travel time information, it is necessary to estimate the single section travel time between consecutive entry and exit ramps. This will also provide valid information for all drivers who pass through this highway section (regardless of whether they have the same origin – destination itinerary or not), and could also enable incident detection applications by tracking down the conflictive highway sections.

One possible method to estimate the single section travel time could be to include only measurements between consecutive entry and exit points into the database. This solution, used in the Italian “AutoTraf” system [2], may reduce excessively the amount of available data in certain sections of the network, where the volume of traffic entering and leaving the highway at consecutive ramps is low, but there is a large volume of through traffic. To overcome the problem of insufficient toll tickets data, the Italian highway operators have installed roadside beacons in the main highway trunk to detect the vehicles equipped with an ETC system tag. The data on vehicles detected by the beacons complement the toll ticket data in these sections.

However, the Italian solution implies a high cost and does not account for the “exit time” (i.e. the time required to leave the highway). The exit time includes the time required to travel

along the exit ramp (deceleration and overcoming the distance along the ramp) plus the time required to pay the fee at the toll gate (perhaps with a small queue). Then, if the time to travel along a particular route, composed of several single sections, is calculated by simply adding the single section travel times, the resulting itinerary travel time would be excessive, because it would include as many exit times as single sections compose the itinerary.

The algorithm presented in this part of the paper proposes a new approach for estimating the single section travel times without reducing the amount of available data, and makes it possible to split this time into the main highway trunk travel time and the exit time (see Fig. 3), without any additional cost. The estimated exit time is a very useful measure for highway operators, as it is an indicator of the toll plazas' level of service.

FIGURE 3 Highway travel time definition.

3.1. Notation and Formulation for the Toll Ticket Travel Time Algorithm

For each particular vehicle “ k ” running along a highway with a closed tolling system (see Fig. 4), the travel time spent on its itinerary between “ i ” (origin) and “ j ” (destination) expressed as “ $t_{i,j,k}$ ” can be obtained by matching the entry and exit information recorded in its toll ticket.

FIGURE 4 Highway ramps diagram with a closed tolling system.

The average travel time for the itinerary in a particular time period “ p ” (e.g. 1 hour) can be obtained by averaging the travel times of all vehicles that have entered the highway within this time period and have traveled along the same itinerary “ (i,j) ”.

$$t_{i,j}^{(p)} = \frac{\sum_{k=1}^{n_i^{(p)}} t_{i,j,k}^{(p)}}{n_i^{(p)}} \quad \forall i = 0, \dots, m-1 \quad \forall j = 1, \dots, m \quad \forall p = 0, \dots, 23 \quad (9)$$

Where: (p) is an hourly time period in relation to vehicle entrances to the highway.

$t_{i,j,k}^{(p)}$ is the travel time for the itinerary “ i,j ” for a particular vehicle “ k ” that has entered the highway within the time period “ p ”.

$t_{i,j}^{(p)}$ is the average travel time for the itinerary “ i,j ” in a particular hourly time period “ p ”.

$n_i^{(p)}$ is the number of vehicles that have entered the highway at the toll plaza “ i ” within the time period “ p ”.

Obviously, outliers should not be considered in the calculation of “ $t_{i,j}^{(p)}$ ”. A value of

“ $t_{i,j,k}^{(p)}$ ” could be considered as an outlier when:

$$t_{i,j,k}^{(p)} < t_{i,j}^{(p)} - 3\sigma_{t_{i,j}^{(p)}} \quad \text{or} \quad t_{i,j,k}^{(p)} > t_{i,j}^{(p)} + 3\sigma_{t_{i,j}^{(p)}} \quad (10)$$

Where:

$$\sigma_{t_{i,j}^{(p)}} = \sqrt{\frac{\sum_{k=1}^{n_i^{(p)}} (t_{i,j,k}^{(p)} - t_{i,j}^{(p)})^2}{n_i^{(p)} - 1}} \quad (11)$$

These outliers must be eliminated from the series of measurements of each time period. From these calculations, the average travel time for a particular itinerary in a particular time period “ $t_{i,j}^{(p)}$ ” is obtained.

FIGURE 5 Outlier effects on hourly averaged travel times.

The next step is to calculate the single section travel time (i.e. travel time between consecutive entry and exit ramps) and the exit time (i.e. the time required to travel along the exit link plus the time required to pay the fee in the toll plaza).

In general, the average travel time “ $t_{i,j}$ ” can be divided in two parts: the section travel time “ $t_{s(i,j)}$ ” and the exit time “ $t_{ex(j)}$ ” (see Fig 3).

$$t_{i,j} = t_{s(i,j)} + t_{ex(j)} \quad (12)$$

If we consider the highway stretch between entrance 0 and exit 1:

$$t_{0,1} = t_{s(0,1)} + t_{ex(1)} \quad (13)$$

Then it can be seen that subtracting different travel times of selected itineraries, the single section travel times and the exit times can be obtained (see Fig 6). Then for the (0,1) itinerary:

$$t_{s(0,1)} \approx t_{0,2} - t_{1,2} \approx t_{0,3} - t_{1,3} \approx \dots \quad (14)$$

$$t_{ex(1)} = t_{01} - t_{s(0,1)} \quad (15)$$

FIGURE 6 Section (0,1) travel time estimation.

Note that for sections with an entrance different from the initial toll plaza, equation 12 should be rewritten as:

$$t_{i,j} = t_{en(i)} + t_{s(i,j)} + t_{ex(j)} \quad \forall i = 1, \dots, m-1 \quad \forall j = 2, \dots, m \quad (16)$$

Where: $t_{en(i)}$ is the “entrance time” (i.e. the time required to travel along the entrance link)

In the present paper it is assumed that the entrance time “ $t_{en(i)}$ ” is small enough in relation to both the section travel time “ $t_{s(i,j)}$ ” and the exit time “ $t_{ex(j)}$ ” to be rejected. Then, in a general

expression for all entry and exit points, the average single section travel times and the average exit times can be calculated for each stretch as:

$$t_{s(i,i+1)} = \frac{\sum_{j=i+2}^m (t_{i,j} - t_{i+1,j})}{m - (i + 1)} \quad \forall i = 0, \dots, m - 2 \quad (17)$$

Where “ m ” is the last toll plaza on the highway, and “ $t_{s(i,i+1)}$ ” is the average travel time for the single section $(i, i+1)$.

To obtain the exit time we only need to subtract this single section travel time from the total itinerary travel time in adjacent entrance/exit points. Then:

$$t_{ex(i+1)} = t_{i,i+1} - t_{s(i,i+1)} \quad (18)$$

Where “ $t_{ex(i+1)}$ ” is the average exit time for the $(i+1)$ toll plaza.

It can be seen that the calculation of a single section travel time results from all the vehicles entering in the entrance point origin of the section, except those traveling only in the considered stretch. Those vehicles are the ones considered in the calculation of the exit time of the section. The algorithm does not consider the vehicles traveling along the stretch but that have entered at a previous entrance.

Note that considering long trips, for instance longer than 3 single sections (i.e. $j-i > 3$) in the calculation of the single section travel times (equation 17) implies an increase in the information delay (because the application of equation 17 requires that all the considered vehicles have left the highway). On the other hand, long trips imply an increase in the standard deviation of the average itinerary travel time (equation 11), due to the higher probability of stops on a long trip. These considerations suggest that for some applications (e.g. real time application) the basic algorithm should be restricted to short trip data. For this situation, equation 17 should be expressed as:

$$t_{s(i,i+1)} = \frac{\sum_{j=i+2}^{i+3} (t_{i,j} - t_{i+1,j})}{2} \quad \forall i = 0, \dots, m-3 \quad (19)$$

$$t_{s(m-2,m-1)} = t_{m-2,m} - t_{m-1,m} \quad \text{for the last but one section} \quad (20)$$

Moreover it must be taken into account that the last section travel time “ $t_{m-1,m}$ ” cannot be split into the main highway trunk travel time and the exit time with the proposed algorithm. Nevertheless, this lack of information is not so important, because the last toll plaza is usually located in the main highway trunk and all the vehicles traveling along the last stretch must go through this toll plaza. In such a way, the interesting information for the driver in this last stretch of the highway is the total aggregated travel time, including both the main trunk travel time and the exit time. On the other hand, the exit time in the last toll plaza would be useful information for the highway operator in order to determine the level of service of this last toll plaza.

4. DATA FUSION FROM MULTIPLE DATA SOURCES

To improve the performance of the three previously presented algorithms, a data fusion system is proposed. Each one of the travel time estimation methods imply a margin of error, related to the sensor technologies and to the implemented algorithms. The performance of the sensors depends on the variable that is being monitored and on the traffic flow. The algorithm error depends also on the traffic flow and on the type of travel time estimation used (RTT - Reconstructed Travel Time or ITT -Instantaneous Travel Time).

4.1. Data Fusion techniques

Data fusion is a compendium of different mathematical techniques to improve the robustness of a travel time estimation system, improving also its reliability and achieving a uniform temporal and spatial coverage [20].

The fusion operators used are Context Independent [20] and use probabilistic, evidential or fuzzy logic [21].

Two different fusion procedures will be performed. The first one fuses the ITT values obtained from both algorithms related to loop detector data. The second, fuses the PTTs (Predicted Travel Time) obtained from the ITT (loop detectors) and the RTT (toll tickets).

FIGURE 7 Data fusion flow chart.

4.2. First Fusion

This first data fusion process uses a fuzzy logic technique to determine the congestion state, using the speed and its variance as references. The temporal mean speed decreases in congestion conditions while its variance increases. The use of fuzzy logic represents the probability functions of these statements to be true (see Fig 8)

FIGURE 8 Probability functions for the binomial flow state characterization.

The fuzzy logic operator is independent of context, and it increases the accuracy of the determination of the traffic flow state in this binomial characterization (congestion or not).

Once the congestion state is determined, the results (ITT1 and ITT2) from the spot speed algorithm and the cumulative flow balance algorithm are fused using a weighted average

operator. The weight applied to each travel time estimation depends on its associated error. This error is related to the traffic flow condition: congestion or free flow.

The result of this first fusion is a more consistent and reliable ITT. This fusion could be replaced by another one fusing each PTT obtained from every single ITT, but this would require more computational effort to obtain a similar fused PTT.

4.3. Second Fusion

In this section the performance of some different data fusion operators are analyzed. These are probabilistic, evidential and fuzzy logic operators. All the algorithms are independent of the context.

The probabilistic approach uses the Bayesian Theory:

$$p(PTT_i | PTT_1, PTT_2) = \frac{p(PTT_2 | PTT_i)p(PTT_1 | PTT_i)p(PTT_i)}{p(PTT_1)p(PTT_2)} \quad (21)$$

$$i = a, \dots, z$$

Where: PTT_i represents the result of the Data Fusion

PTT_1 represents the PTT obtained from the Loop Data

PTT_2 represents the PTT obtained from the Ticket Data

The a priori probability $p(PTT_i)$ is supposed to be equal to unit. This hypothesis does not give any extra information, but it will improve with the historical data of the road. The probability functions $p(PTT_j | PTT_i)$ are determined during the training of the algorithm depending on the validation results.

The evidential approach uses the generalization of the Bayes Theory, implementing the Dempster Rule.

Finally the fuzzy logic uses a Context Independent Operator to fuse the probability of every independent PTT to belong to any of the fused PTT sets (Fig 9). The higher probability set is chosen as the right one.

FIGURE 9 Probability functions of every independent PTT to belong to any fused sets.

5. MODEL RESULTS AND TRAVEL TIME DISSEMINATION

The proposed travel time estimation method from multiple data sources is currently being applied in the AP-7 toll highway in Spain. The AP-7 highway runs along the Mediterranean cost corridor, from the French border to the Gibraltar strait. Nevertheless, the pilot test is restricted to the north east stretch of the highway from “La Roca del Vallès” toll plaza, near Barcelona, to the French border at “La Jonquera”. This stretch is approximately 120 km long.

Figure 10 provides a graphical summary of the average speeds resulting from the calculated single section travel times. The figure provides average speeds for both directions and for three different time periods. It has to be taken into account that the speed limit on highways in Spain is 120 km/h, and the off peak time speed has been limited according to this legal speed. In this figure it can be observed that the most problematic period was the pm period in the southbound direction. This situation is a result of the massive return to Barcelona city on Sunday afternoon or evening, after spending a day or a weekend at the beach. Note that the average speeds in the single sections before a main highway toll plaza (in the two edges of the stretch), are very low. These low speeds are due to the inclusion of the exit time (i.e. the time required to pay the fee) in these final sections travel time.

FIGURE 10 Graphic summary of average speeds in AP-7 highway (July 10th, 2005 data).

Once probed the accuracy of the proposed travel time estimation method, the dissemination of this traffic information to the highway users is the key factor. Traffic information dissemination techniques can be clearly divided in two main blocks: pre-trip information and on-trip information. Pre-trip information allows trip planning while on-trip information is useful in order to modify the initial planning according to current traffic conditions.

For traffic information to be effective it must be short, concise, quantified and specifically addressed to the receptor. Travel time information itself fulfills the three first conditions, and the dissemination technology must fulfill the last one. Taking into account these criteria, a multicriterion analysis of different traffic information dissemination technologies has been performed (Table 1).

TABLE 1 Multicriterion Analysis of Different Traffic Information Dissemination Technologies

From table 1 results it is stated that car navigators and VMS are the technologies with higher dissemination potentialities. These results are in accordance to the current practices of Spanish operators who are installing VMS panels in most of the primary network. Moreover results also agree with user perceptions, as car navigation devices are currently best selling car items.

6. CONCLUSIONS AND FURTHER RESEARCH

Link travel time is the most appreciated information for road users. The proposed approach for calculating travel times in toll highways using multiple data sources is a simple one and can be

easily put into practice with the existing infrastructure. The scheme uses data obtained from loop detectors and toll tickets on highways with a closed tolling system.

The proposed data fusion method is capable of increasing the robustness and accuracy of each particular travel time estimation algorithm. The final travel time estimation relies on both loop detector data and toll ticket data, so that if one source of information is unavailable or the associated error is too high, the final travel time estimation is still available relying on the best available data.

The results of the pilot test carried out on the AP-7 highway in Spain indicate the suitability of the method for the link travel time estimation in a closed toll highway system.

Moreover, this accuracy in the travel time estimation should make the development of a robust incident detection system possible, by comparing the real time estimations to the recurrent travel times.

Travel time prediction on the basis of the present scheme is also a key factor for future research.

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TABLE 1 Multicriterion Analysis of Different Traffic Information Dissemination Technologies

Mark	Technology	Description	Pre-Trip	On-Trip	Specifically addressed	On demand	User Friendly
10	Car Navigator	On vehicle device RDS-TMC	√	√	√	X	√
10	VMS	Variable Message Signs	√	√	√	X	√
8	Radio broadcasts	Radio bulletin	√	√	X	X	√
7,5	Cellular Phone	Text services	√	√	√	√	=
7	Phone	Traffic Call Center	√	√	√	√	X
2,5	TV Broadcasts	TV bulletin	√	X	X	X	√
2,5	Press	Conflictive days announcements	√	X	X	X	√
2,5	Internet	Online services	√	X	√	√	√
2	Information Points	Service Area information	√	√	√	√	XX

FIGURE 1 Spot speed algorithm required surveillance configuration.

FIGURE 2 Cumulative flow balance algorithm required surveillance configuration.

FIGURE 3 Highway travel time definition.

FIGURE 4 Highway ramps diagram with a closed tolling system.

FIGURE 5 Outlier effects on hourly averaged travel times.

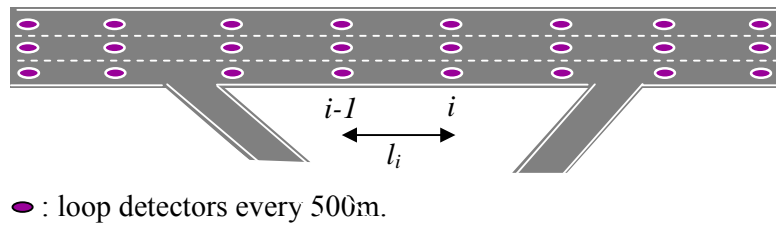
FIGURE 6 Section (0,1) travel time estimation.

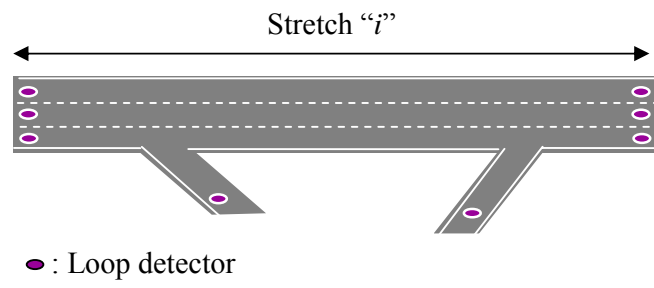
FIGURE 7 Data fusion flow chart.

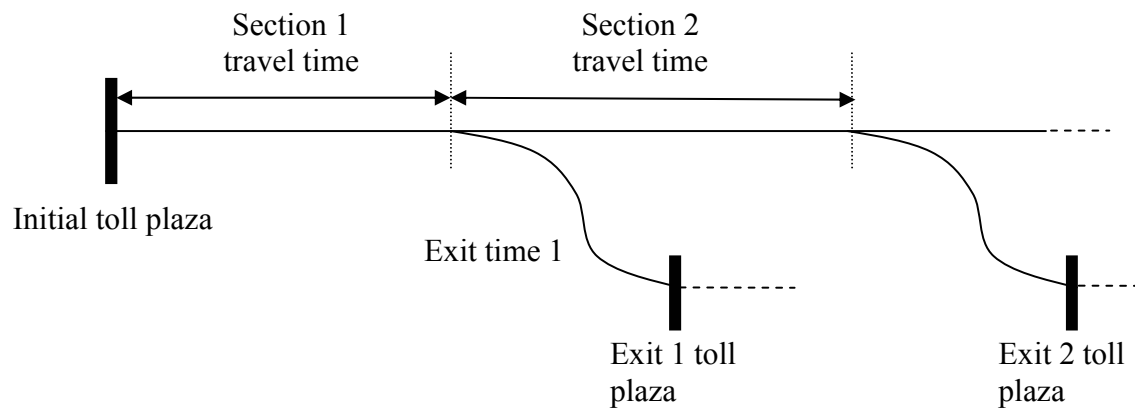
FIGURE 8 Probability functions for the binomial flow state characterization.

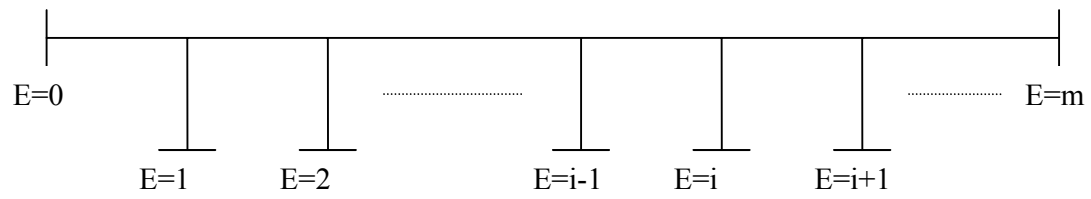
FIGURE 9 Probability functions of every independent PTT to belong to any fused sets.

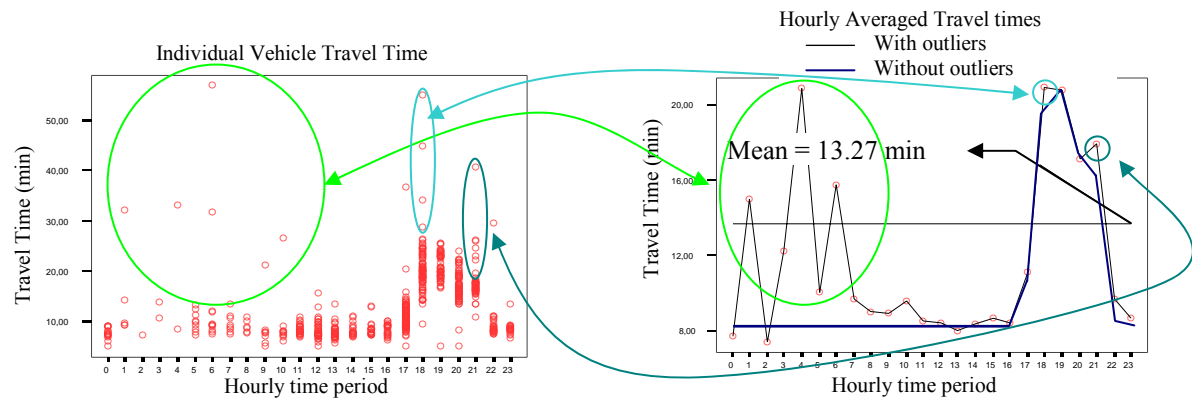
FIGURE 10 Graphic summary of average speeds in AP-7 highway (July 10th, 2005 data).

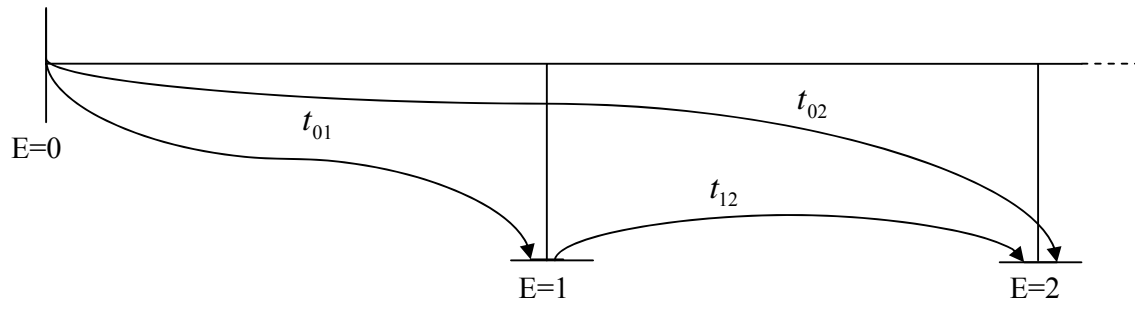


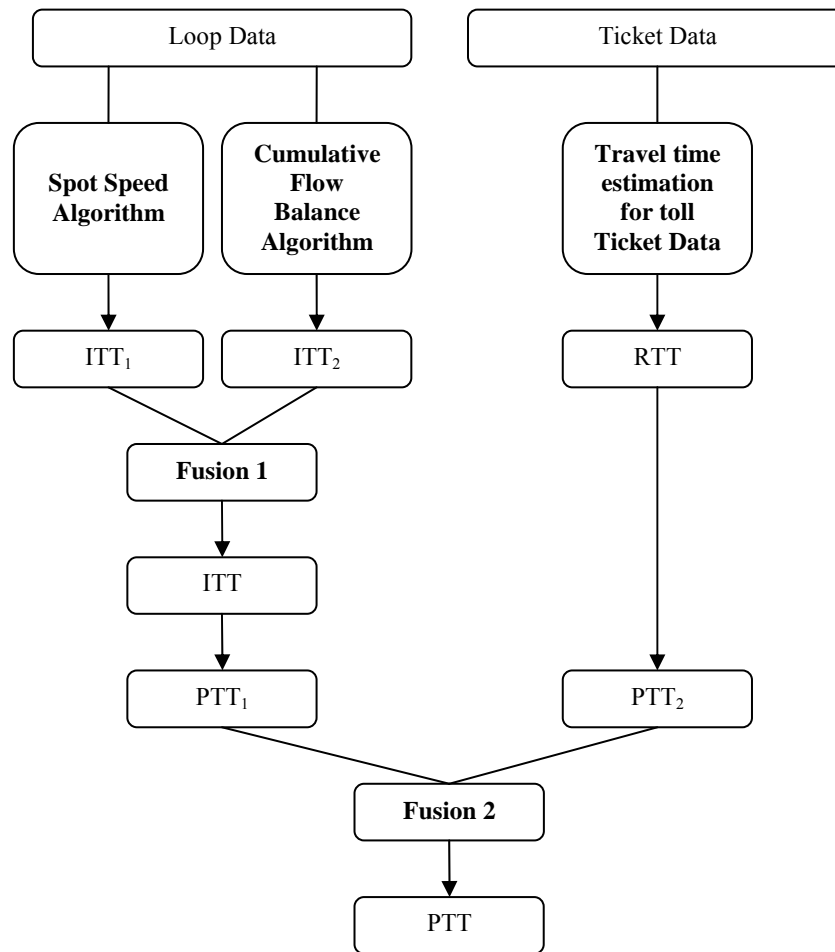


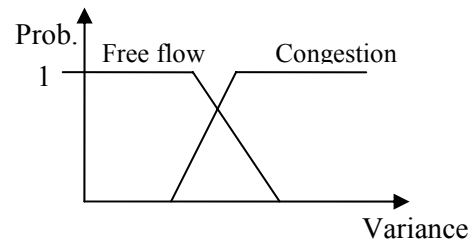
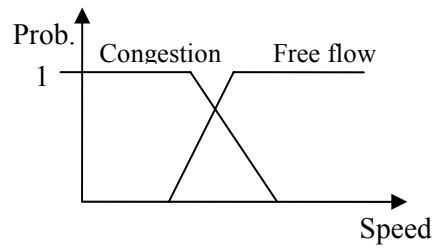


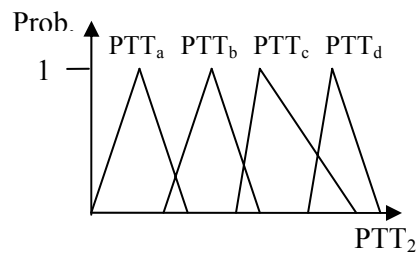
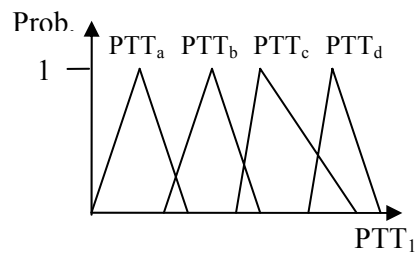












LEGEND					
Peak Hour Speed (Km/h)					
OFF PEAK	PM	AM	AM	PM	OFF PEAK
Southbound			Northbound		

